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EXPRESS ARTICLE

A soft and shape-adaptive electroadhesive composite gripper with proprioceptive and exteroceptive capabilities

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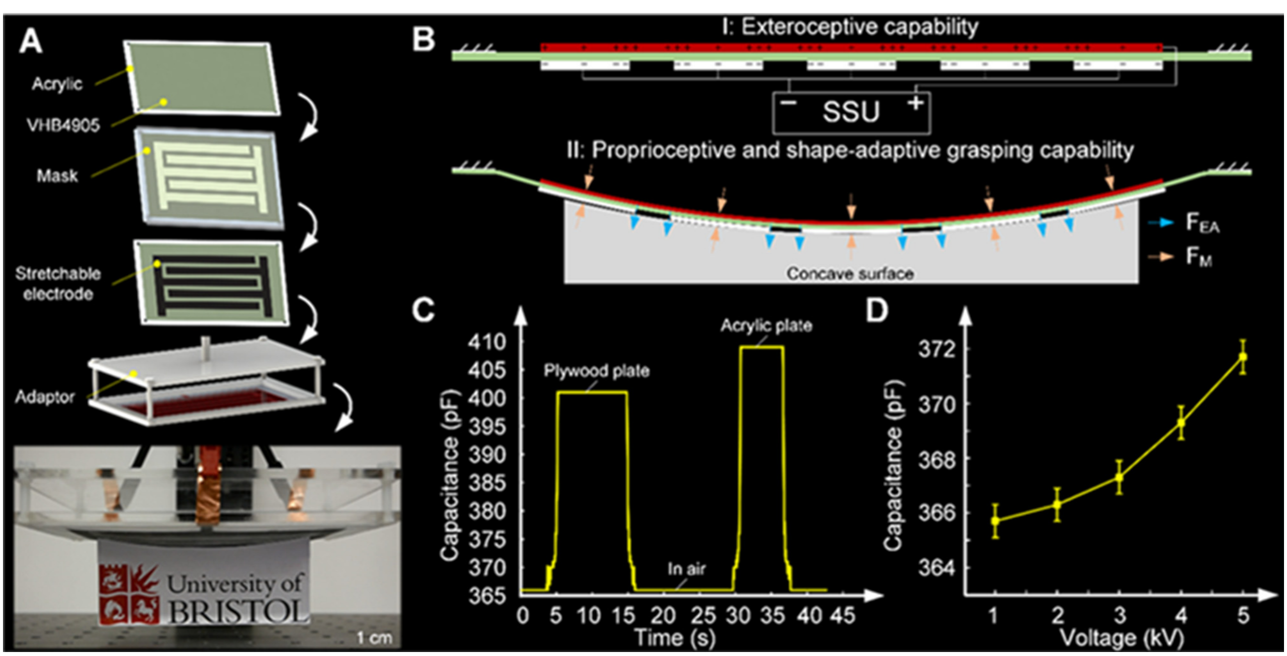
Electroadhesion is a promising adhesion mechanism for robotics and material handling applications with advantages over existing technologies including enhanced adaptability, gentle/flexible handling, reduced complexity, and ultra-low energy consumption. Current electroadhesive (EA) grippers, however, require extra components and their associated electronics to make them sensorially capable. In addition, current planar EA grippers have difficulty adhering to non-planar surfaces and picking up non-flat objects. We present a monolithic, shape-adaptive, and self-sensing EA composite with integral dielectric elastomer actuation (DEA). This new EA-DEA composite gripper is not only proprioceptive (it can sense internal deformations) and exteroceptive (it can sense and differentiate between surfaces that it touches) but can also actively morph and adapt to curved surfaces. By integrating a high voltage self-sensing unit with the EA-DEA composite, coupled gripping and sensing capabilities can be achieved. This is because combined actions of membrane deformations by the Maxwell force and surface attraction by the EA force can be obtained by using only one voltage source due to the employment of a dual-mode parallel-and-coplanar electrode pattern. The proposed approach has the potential to significantly improve the intelligence of EA gripping technologies and increase their use in intelligent material sorting, grasping, and manipulation applications.



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Electroadhesion is an electrically controllable and dynamic electrostatic attraction between an electroadhesive (EA) and a substrate [1,2]. EAs can be employed to grasp/manipulate objects in domains including space, high value manufacturing, robotics, and autonomous systems due to their advantages including enhanced adaptability, gentle/flexible handling, reduced complexity, and ultra-low energy consumption, making them ideal for integration into robotic actuators and grippers [1–8]. However, increased reliability of this technology, taking safety and environmental issues into consideration, requires further and collaborative efforts [2].

Robotics is undergoing a paradigm shift from conventional to soft robotics. In order to integrate EA into soft devices, stretchable EAs are required. Previous stretchable EAs [4] demonstrated that higher adaptability can be achieved by stretchable EAs over non-stretchable configurations, but the structures presented were not active and intelligent. In order to pick-and-place objects in unstructured environments in a robust and safer way, EA systems must be capable of proprioceptive and exteroceptive sensing. Exteroceptive EAs are defined as those which can differentiate material types and apply robust voltages accordingly. Proprioceptive EAs are defined as those which can sense their own deformations/strains. Various sensors have previously been integrated with EA systems to make them exteroceptive [2,5] and proprioceptive [6]. All these EAs, however, require extra sensors and their associated electronics to make them proprioceptive and exteroceptive. Furthermore, shape-adaptive EAs are needed to adhere to curved surfaces or to pick up flexible objects from curved surfaces. Guo et al. proposed a PneuEA gripper, combining a soft pneumatic actuator with a stretchable EA [5]. Shintake et al. combined DEA with EA to fabricate soft grippers capable of manipulating various difficult-to-handle objects [7]. These shape-adaptive EA grippers, however, cannot differentiate materials and adhere to or manipulate concave surfaces using EA capability only.

We present the first monolithic, soft, and shape-adaptive EA-DEA composite gripper with proprioceptive and exteroceptive capabilities. The gripper fabrication and integration procedure is composed of five steps (Fig. A). Firstly, a 0.5 mm thick soft VHB 4905 dielectric membrane (3M, USA) was directly (without pre-stretch) adhered to a laser cut acrylic plate. Secondly, a Cricut cutter was used to produce dual-mode parallel-and-coplanar electrodes that were composed of a single uniform electrode on one side and spaced coplanar electrodes on the other [9]. These were then bonded to the top and bottom of the membrane. The effective dimensions of both the top and bottom electrodes were 140 mm × 70 mm. For the bottom electrodes an inter-digited arrangement was used of width of 10 mm, spacing of 5 mm, and thickness of 65 μm. Thirdly, stretchable and curable conductive silicon electrodes were doctor-blade deposited through the masks. The customized electrode material was made by mixing 20% wt. carbon grease (MG Chemicals, Canada) with Ecoflex 00-10 (Smooth-On Inc., USA). The materials used need to be suitable for DEA and EA actuation separately and simultaneously [9]. As a result, the material thickness, compliance, and conductivity should be carefully tailored to achieve optimal performance. Fourthly, the masks were peeled off and the three electrodes were connected with three copper tapes. The EA-DEA composite was then cured in an oven at 50 °C for 4 h. Finally, the top electrode was connected to the positive output of a PC-controlled high voltage self-sensing unit (SSU, The University of Auckland) [10] and the bottom two were connected to the negative output. The complete composite gripper was mounted on a PC-controlled vertical stage. An SSU was used to simultaneously supply the high voltages needed for DEA/EA actuations and measure the capacitance when the gripper is touching different surfaces and morphing.

When applying a high voltage to the EA-DEA electrodes, the induced Maxwell force ($\boldsymbol{F_M}$) between the top and bottom electrodes deforms the structure, causing the membrane to bend out-of-plane towards the object to be lifted; simultaneously an induced EA force ($\boldsymbol{F_{EA}}$) is developed at the bottom electrodes, which attracts objects to the gripper (Fig. B). At larger the applied voltages, larger $\boldsymbol{F_M}$ and $\boldsymbol{F_{EA}}$ are obtained. By selectively powering the electrodes, dielectric elastomer actuation and electroadhesion can be achieved. The interplay between these phenomena also resulted in morphing and gripping functions that were controlled by a single voltage input. The bottom coplanar electrodes can be used to differentiate materials at low voltages (due to differing fringing fields interactions) and to pick-and-place objects at high voltages. The EA-DEA structure can also be used to sense and handle concave objects as shown in Fig. A (a 5.2 g concave surface with a contact area of 40 mm × 120 mm and radius of 23°).

The on-line capacitance values facilitate classification of the material in contact with the gripper and quantification of membrane deformations under DEA actuation. When applying 1 kV to the EA-DEA electrodes, different capacitance values were obtained when the gripper was in air and touching an acrylic plate and plywood, respectively, as shown in Fig. C. During this process, a preload of 15 N was applied between the gripper and substrate materials, and the temperature and humidity were controlled at 21.9 ± 0.1 °C and 45 ± 1%, respectively. When applying a stepped voltage from 1 to 5 kV to the gripper, a monotonically increasing capacitance was measured, as shown in Fig. D. It should be noted that increased coplanar electrode pairs would enhance the sensitivity of these capacitance readings.

These results demonstrate that the new monolithic, shape-adaptive, and self-sensing EA-DEA composite gripper is not only capable of sensing proprioceptive (intrinsic deformations) and exteroceptive (contact indications and different materials) stimuli but also of morphing to concave surfaces. These characteristics can be exploited for intelligent industrial material sensing and EA handling of objects including fabrics, bowls, and lenses.

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